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U-Boot – Bootloader for IoT Platform?

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- Maintainer of ARC architecture in U-Boot
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  - Linux kernel
  - Buildroot
  - OpenEmbedded
  - OpenWrt
  - uClibc etc

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Agenda

U-Boot for IoT device

Shrinking memory footprint

Execution from ROM

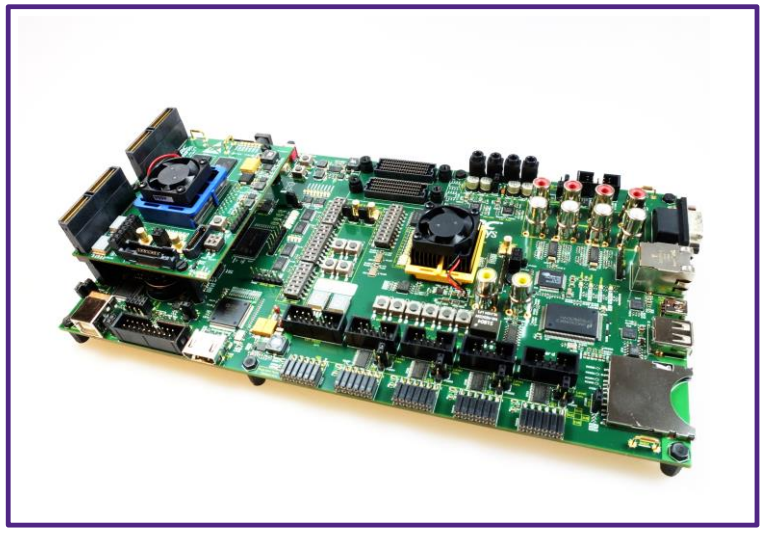
Run-time issues

Previous ARC boards with U-Boot

Single-board computers with Linux

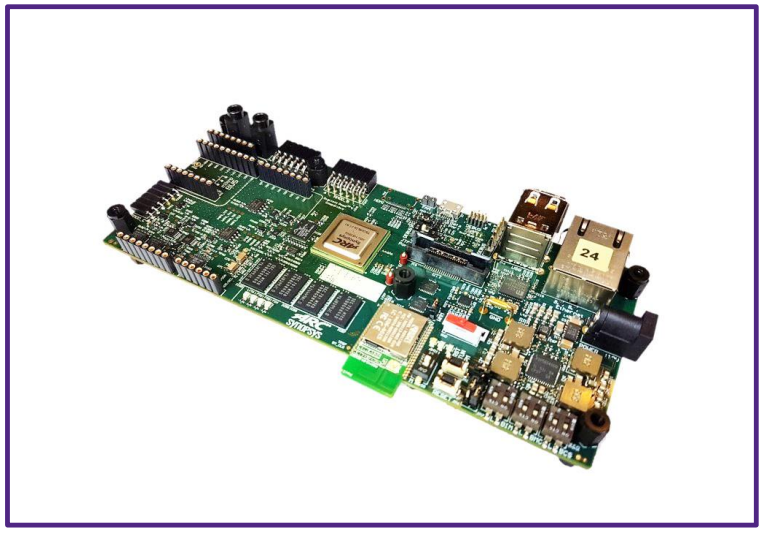
AXS103

- Dual-core ARC HS38 @ 100 MHz in FPGA
- BootROM
- 2 GiB of DDR



HSDK

- Quad-core ARC HS38 @ 1 GHz in silicon
- BootROM
- 4 GiB of DDR



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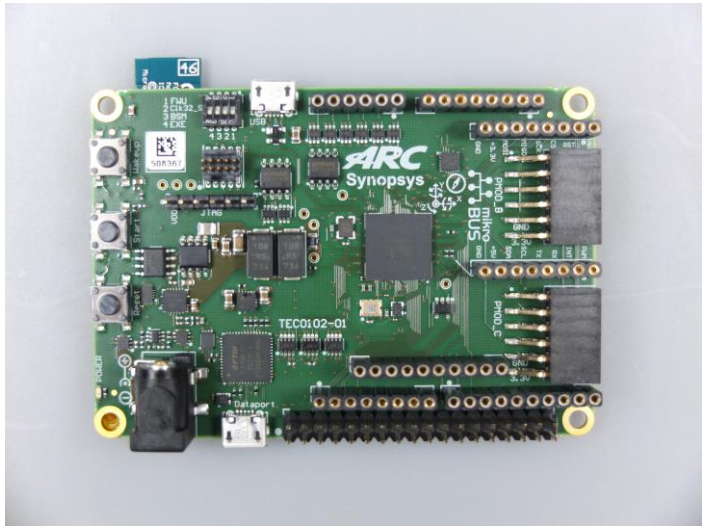
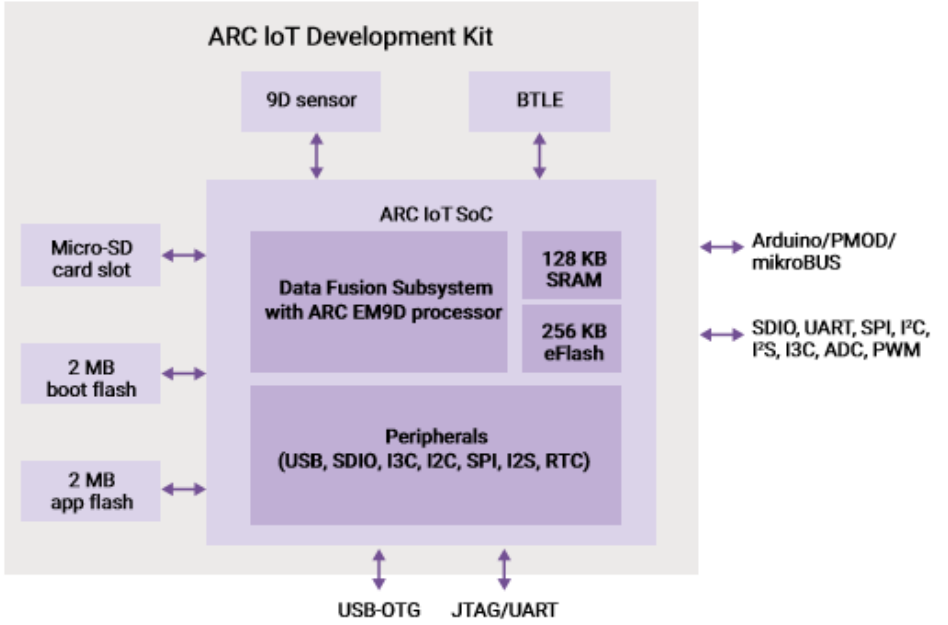
New board – new fun

Meet IoT development kit

- ARC EM9D @ 150 MHz
- Memories:
  - **eFlash** **256 KiB @ 0x0000_0000**
  - **ICCM** **256 KiB @ 0x2000_0000**
  - **SRAM** **128 KiB @ 0x3000_0000**
  - DCCM 128 KiB @ 0x8000_0000
  - SPI flash 2 MiB
- Peripherals:*
  - SD-card (DW MobileStorage)
  - USB OTG (DW USB OTG)
  - Serial port (DW APB UART)





* The board features many more peripherals but we are only listing those relevant to the bootloader here

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Why U-Boot

Add support of a new board in the blink of an eye

- Mature and well-known bootloader
- Supports:
  - 12 CPU architectures
  - Lots of peripherals: UART, SPI, I2C, Ethernet, SD, USB …
  - File-systems: Fat, Ext, Yaffs2, Btrfs, ubifs …
  - Networking protocols: TFTP, NFS, DHCP
- "Device-tree" used for drivers initialization
- Allows for flexible scripting in "hush" shell
- Allows re-use of its stdio and C run-time libs by user applications

```
$ git show --stat --pretty=oneline 5396e8b
5396e8b arc: Add support for IoT development kit
 arch/arc/Kconfig                           |   5 ++++
 arch/arc/dts/Makefile                      |   1 +
 arch/arc/dts/iot_devkit.dts                |  45 ++++++++++++++++++++++
 board/synopsys/iot_devkit/Kconfig          |  12 ++++++++
 board/synopsys/iot_devkit/MAINTAINERS      |   5 ++++
 board/synopsys/iot_devkit/Makefile         |   7 +++++
 board/synopsys/iot_devkit/config.mk        |   2 ++
 board/synopsys/iot_devkit/iot_devkit.c     | 168 ++++++++++++++++++++++
 board/synopsys/iot_devkit/u-boot.lds       |  77 ++++++++++++++++++++++
 configs/iot_devkit_defconfig               |  38 ++++++++++++++++++++++
 include/configs/iot_devkit.h               |  84 ++++++++++++++++++++++
 11 files changed, 444 insertions(+)
```

Starting point: 422 KiB total

- DW USB OTG & DW MMC drivers
- Read/write FAT file-system
- Built-in .dtb

```
$ size u-boot
   text    data     bss     dec     hex filename
 257129    9372  155928  422429   6721d u-boot
```

```
CONFIG_ARC=y
CONFIG_ISA_ARCV2=y
CONFIG_CPU_ARCEM6=y
CONFIG_TARGET_IOT_DEVKIT=y
CONFIG_CMD_MMC=y
CONFIG_CMD_USB=y
CONFIG_CMD_FAT=y
CONFIG_OF_CONTROL=y
CONFIG_OF_EMBED=y
CONFIG_ENV_IS_IN_FAT=y
CONFIG_ENV_FAT_INTERFACE="mmc"
CONFIG_ENV_FAT_DEVICE_AND_PART="0:1"
CONFIG_DM=y
CONFIG_MMC=y
CONFIG_MMC_DW=y
CONFIG_DM_SERIAL=y
CONFIG_SYS_NS16550=y
CONFIG_USB=y
CONFIG_DM_USB=y
CONFIG_USB_DWC2=y
CONFIG_USB_STORAGE=y
```


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Shrinking memory footprint

We only have 256 KiB of ROM and 128 KiB of RAM

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Disable useless options: 366 KiB total

As simple as deselecting items in `menuconfig`

- No plans to load OS
- No plans to use flash (as of now)
- There's no Ethernet controller
- No memory to load application from Elf
  - Load Elf
  - Copy sections from Elf to RAM
- No need to load via serial port

```
# CONFIG_CMD_BOOTD is not set
# CONFIG_CMD_BOOTM is not set
# CONFIG_CMD_ELF is not set
# CONFIG_CMD_XIMG is not set
# CONFIG_CMD_FLASH is not set
# CONFIG_CMD_LOADB is not set
# CONFIG_CMD_LOADS is not set
# CONFIG_NET is not set
```

```
$ size u-boot
   text    data     bss     dec     hex filename
 216009    7544  142468  366021   595c5 u-boot
```


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Get rid of dead code: 311 KiB total

Might require changes in sources

- Put all functions, global & static variables in their own sections and strip unused on final linkage.
- Should be enabled by default for all architectures and boards in U-Boot except toolchain doesn’t support it.
- Was not the case for ARC – fixed now [fac4790491f6 (“arc: Eliminate unused code and data with GCC's garbage collector”)]

```
CPPFLAGS += -ffunction-sections -fdata-sections
LDFLAGS += --gc-sections
```

```
$ size u-boot
   text    data     bss     dec     hex filename
 163532    6948  140928  311408   4c070 u-boot
```


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Shrink statically allocated buffers: 188 KiB total

- `tmpbuf_cluster` & `get_contents_vfatname_block` of 65 KiB each!
- `CONFIG_FS_FAT_MAX_CLUSTSIZE=4096`
- Save 120 KiB of memory!

```
$ size u-boot
   text    data     bss     dec     hex filename
 163532    6948   18048  188528   2e070 u-boot
```

```
$ nm --size-sort --reverse-sort u-boot | head -n 5
00010000 b tmpbuf_cluster
00010000 B get_contents_vfatname_block
00001414 b hist_lines
00000a96 t do_fdt
00000812 t set_contents

#define MAX_CLUSTSIZE  CONFIG_FS_FAT_MAX_CLUSTSIZE
static __u8 tmpbuf_cluster[MAX_CLUSTSIZE]
__aligned(ARCH_DMA_MINALIGN);
__u8 get_contents_vfatname_block[MAX_CLUSTSIZE]
```


Compile-time optimizations summary: /2 size

Memory foot-print reduced from 422 to 188 KiB (saved 234 KiB)

- Analyze
  - Main contributors were huge statically allocated buffers
  - Primary tools:
    - `bloat-o-meter` (https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/tree/scripts/bloat-o-meter)
    - `size`
    - `nm`
- Be practical
  - Unused options might add to memory usage significantly (56 KiB in our case)
- Use advanced features of the toolchain
  - 5% size reduction due to dead code elimination
  - Link Time Optimization (LTO) might help a bit more

Execution from ROM

Relocation & memory partitioning

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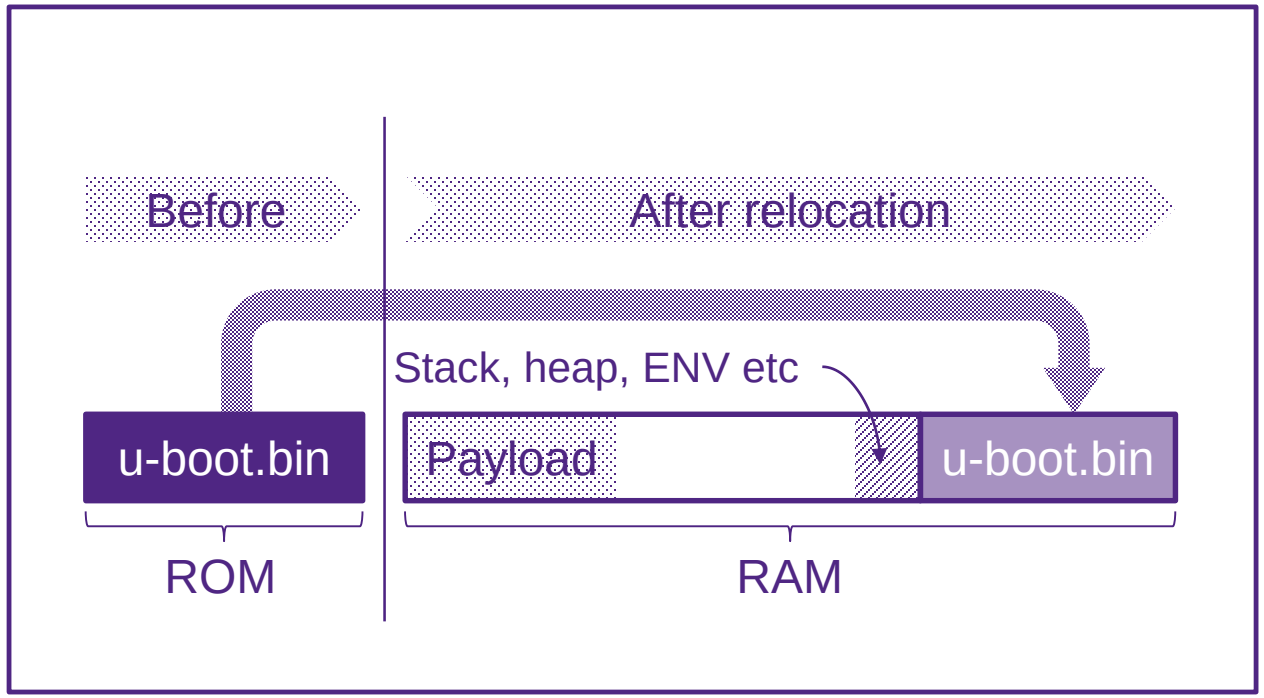
[Self-] relocation

Fundamental feature of U-Boot

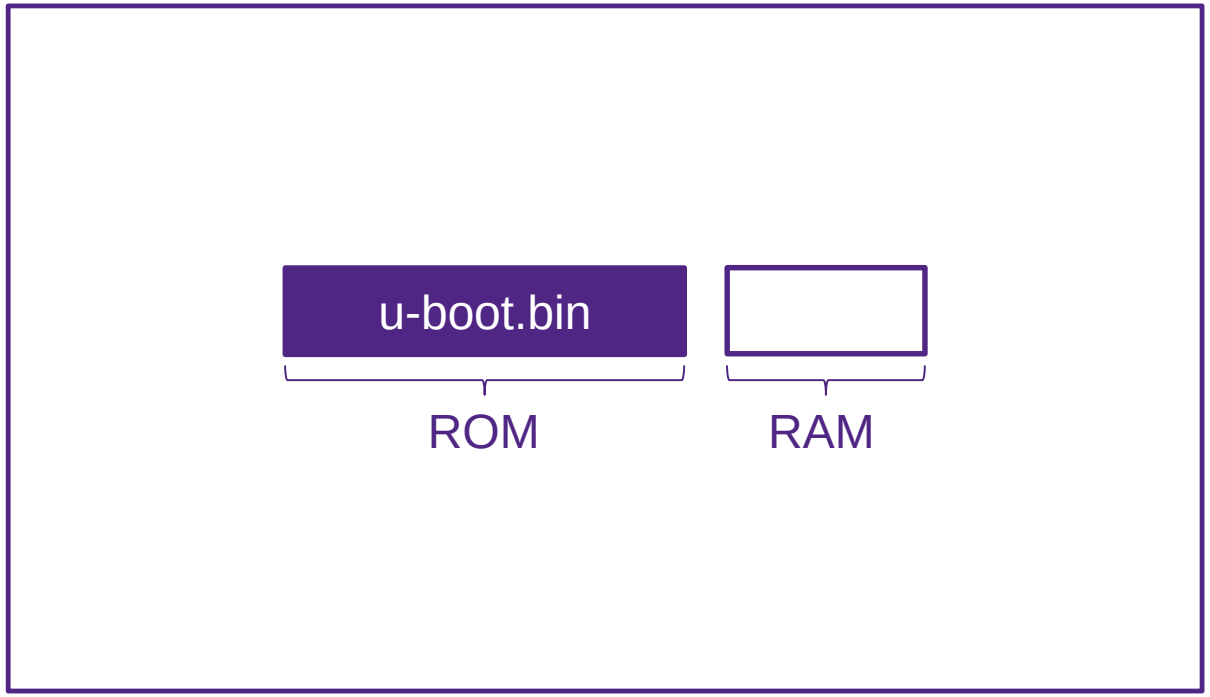
- Why relocation?
  - RAM is much larger
  - DDR might require initialization before use
  - We'll need RAM anyways so why not?
- 2 major stages:
  - Pre-relocation (`common/board_f.c`)
    Execute code from ROM/flash with limited RAM options:
    - On-chip SRAM
    - Locked D$ lines (x86)
    - DDR (sometimes)
  - After-relocation (`common/board_r.c`)
    Executing from RAM (usually DDR)



Skip relocation*

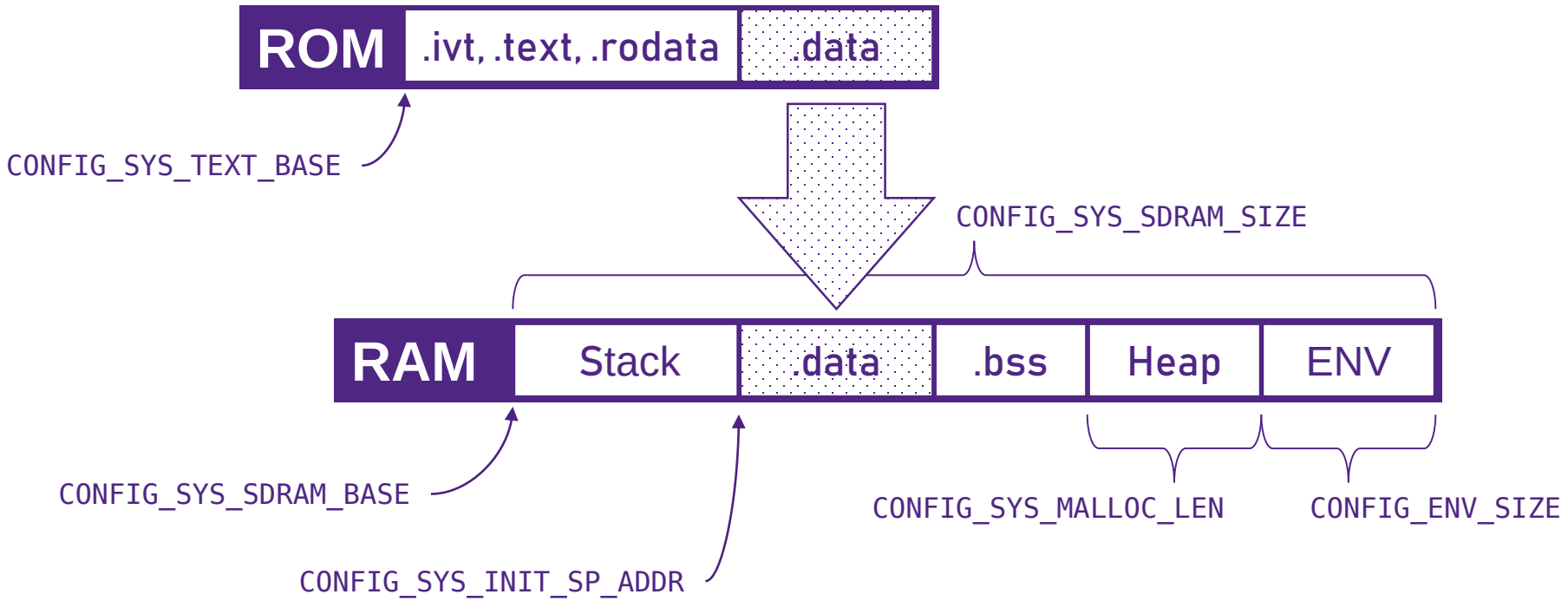
What if RAM size < ROM size = u-boot.bin

- Only supported for ARC as of today
- Add support for your architecture: `264d298fda39 ("arc: Introduce a possibility to not relocate U-boot")`
- In platform/board code signal your intention
- Copy .data from ROM to RAM
- Keep executing code from ROM/flash
- Use RAM only for data
  - Heap
  - Stack
  - .data
  - Environment
  - Payload



Memory partitioning

Standard U-Boot `CONFIG_xxx` constants



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Definition of derived constants

configs/iot_devkit.h

```
#define CONFIG_SYS_MONITOR_BASE         CONFIG_SYS_TEXT_BASE

#define SRAM_BASE                       0x30000000
#define SRAM_SIZE                       SZ_128K
#define DCCM_BASE                       0x80000000
#define DCCM_SIZE                       SZ_128K

#define CONFIG_SYS_SDRAM_BASE           DCCM_BASE
#define CONFIG_SYS_SDRAM_SIZE           DCCM_SIZE
#define CONFIG_SYS_INIT_SP_ADDR         (CONFIG_SYS_SDRAM_BASE + SZ_32K)
#define CONFIG_SYS_MALLOC_LEN           SZ_64K
#define CONFIG_SYS_BOOTM_LEN            SZ_128K
#define CONFIG_SYS_LOAD_ADDR            SRAM_BASE
#define ROM_BASE                        CONFIG_SYS_MONITOR_BASE
#define ROM_SIZE                        SZ_256K
#define RAM_DATA_BASE                   CONFIG_SYS_INIT_SP_ADDR
#define RAM_DATA_SIZE                   CONFIG_SYS_SDRAM_SIZE - \
                                        (CONFIG_SYS_INIT_SP_ADDR - \
                                        CONFIG_SYS_SDRAM_BASE) - \
                                        CONFIG_SYS_MALLOC_LEN - \
                                        CONFIG_ENV_SIZE
```

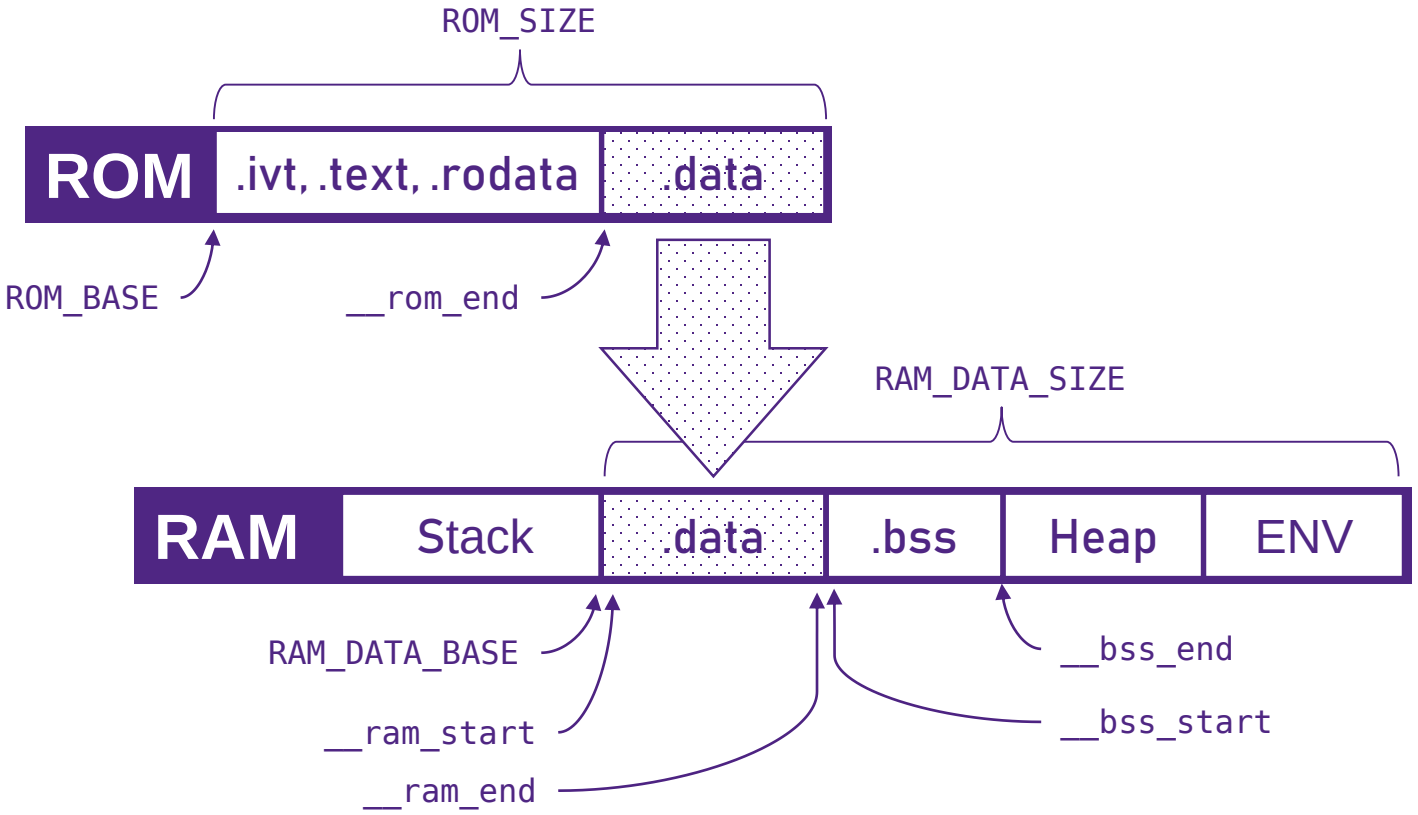
board/synopsys/iot_devkit/u-boot.lds

```
MEMORY {
    ROM : ORIGIN = ROM_BASE, LENGTH = ROM_SIZE
    RAM : ORIGIN = RAM_DATA_BASE, LENGTH = RAM_DATA_SIZE
}
SECTIONS
{
            . = CONFIG_SYS_MONITOR_BASE;
            .ivt : { *(.ivt); } > ROM
            .text : { *(.text*); } > ROM
            .rodata : { *(.rodata*); } > ROM
             __rom_end = .;
            .data : {
                        __ram_start = .;
                        *(.data*)
                        __ram_end = .;
            } > RAM AT > ROM
            .bss : {
                        __bss_start = .;
                        *(.bss*)
                        __bss_end = .;
            } > RAM
```

https://sourceware.org/binutils/docs/ld/Output-Section-LMA.html#Output-Section-LMA

Memory partitioning

Derived constants



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Required quirks

They are not too many

- Signal intention to skip relocation
  - Set `GD_FLG_SKIP_RELOC` flag
- Copy `.data` section from ROM to RAM
- Zero `.bss` as usual in `clear_bss()`

```
/* 1. Don't relocate U-Boot */
gd->flags |= GD_FLG_SKIP_RELOC;

/* 2. Copy data from ROM to RAM */
u8 *src = __rom_end;
u8 *dst = __ram_start;
while (dst < __ram_end)
            *dst++ = *src++;

/* 3. Zero .bss as usual in clear_bss() */
size_t len = (size_t)&__bss_end - (size_t)&__bss_start;
memset((void *) &__bss_start , 0x00, len);
```


Run-time issues

-ENOMEM

Even though we boot to command prompt "`usb start`" fails

- Problem
  - Driver attempts to allocate 64 KiB buffer
- Fix
  - 42637fdae833 ("usb: dwc2: Allow selection of data buffer size")
  - Set CONFIG_USB_DWC2_BUFFER_SIZE = 16 (instead of default 64)
- Hint
  - Check malloc() return value early!

```
starting USB...
USB0:   probe failed, error -12
USB error: all controllers failed lowlevel init


[14] malloc(bytes = 66328) = dlmalloc.c!1241
[13] memalign()+0x78 = dlmalloc.c!1922
[12] alloc_priv()+0x1a = device.c!269
[11] device_probe()+0x9c = device.c!325+0x6
[10] usb_init()+0xa2 = usb-uclass.c!276
[ 9] do_usb_start()+0xc = usb.c!586+0x4
[ 8] do_usb()+0x4e = usb.c!657
...


#define DWC2_DATA_BUF_SIZE            (64 * 1024)
struct dwc2_priv {
            uint8_t aligned_buffer[DWC2_DATA_BUF_SIZE];
            ...
}
```


Stack overflow

Compared to malloc we don't control stack size

- Problem
  - Instead of 78 bytes for `struct legacy_mbr` we allocate 78 * 512 ("`blksz`") = 40KiB on stack
- Fix
  - 8639e34d2c5e ("part: Allocate only one legacy_mbr buffer")
- Hints
  - `ALLOC_ALIGN_BUFFER()`, `ALLOC_CACHE_ALIGN_BUFFER()` allocate buffers on stack
  - Use Memory Protection Unit (MPU) if possible
  - Locate stack right after non-existing memory or at least read-only region to get early exception

```
IoTDK# usb start
starting USB...
USB0:   scanning bus 0 for devices...


[20] part_test_dos() = part_dos.c!90
[19] part_init()+0x30 = part.c!241
[18] usb_stor_probe_device()+0xfc = usb_storage.c!280
[17] device_probe()+0x84 = device.c!416

#define ALLOC_CACHE_ALIGN_BUFFER(type, name, size) \
                        char name[size * sizeof(type)]


static int part_test_dos(struct blk_desc *dev_desc)
{
            ALLOC_CACHE_ALIGN_BUFFER(legacy_mbr, mbr,
                                     dev_desc->blksz);
...
}
```


Conclusions

U-Boot could be ported on very memory-constrained system

- 200 KiB of ROM and 128 KiB of RAM is enough for full-scale U-Boot
  - USB and MMC drivers
  - FAT file-system with write support
- With tools, trials & errors it's possible to shrink memory footprint a lot
  - With vary basic tools it's possible to identify large statically-allocated objects
  - Allocations happen in run-time as well
  - Fixes and improvements to generic code might be required
- Special measures required to skip relocation
  - Requires changes in generic & architecture-specific code
- Run-time issues are mostly due to attempts to allocate more memory than available

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Thank You